

MARKED-UP VERSION OF
ENGLISH TRANSLATION OF
INTERNATIONAL APPLICATION
AS ORIGINALLY FILED

DESCRIPTION

METHOD OF DRIVING ULTRASONIC TRANSDUCER

BACKGROUND OF THE INVENTION

1. ~~Technical~~ Field of the Invention

[0001] —The present invention relates to a method of driving an ultrasonic transducer for use in measuring sound ~~velocity~~speed in a liquid ~~or the like~~ by transmitting and receiving an ultrasonic wave.

2. Description of the Related Art

~~Background Art~~

[0002] —In general, an ultrasonic transducer has a piezoelectric resonator including a pair of electrodes which sandwich~~formed by sandwiching~~ a piezoelectric body, and is provided with a backing layer on the back surface of one of the electrodes of this piezoelectric resonator (for example, see Japanese Unexamined Patent Application Publication No. 2003-259490 (~~refer to Patent Document 1~~)). When a drive signal is applied across the pair of electrodes, the piezoelectric resonator is excited to transmit an ultrasonic wave. On the other hand, when an ultrasonic wave is received, the piezoelectric resonator converts the vibration into an electrical signal, and outputs the electrical signal. ~~In addition it. Also,~~

the backing layer is provided in order to absorb and attenuate an ultrasonic wave emitted from the piezoelectric resonator to the back surface at the time of excitation~~time~~.

[0003] ——When sound speeds in various liquids are measured using such an ultrasonic transducer, a pair of ultrasonic transducers are disposed ~~opposite~~ at a predetermined distance from one another, and an ultrasonic wave is transmitted from one of the ultrasonic transducers. The other of the ultrasonic transducers receives the ultrasonic wave that has passed through a liquid. A measurement circuit measures the time required for transmission and receiving, and the sound speed in the liquid is calculated on the basis of the measured time and the ~~opposed~~ distance between both of the ultrasonic transducers.

[0004] ——In this case, when the difference of the acoustic characteristic impedance (acoustic characteristic impedance) of the piezoelectric resonator and that of the backing layer disposed on the back surface thereof is large, the reflection of a sound wave occurs on the boundary surface of both layers to cause resonance in the piezoelectric body, and thus, a phenomenon, in which vibration continues without converging in a short time, namely so-called ringing, occurs due to the resonance. When this ringing occurs~~arises~~, a ringing component is included in the signal of the received wave which causes increases into~~increase~~ measurement errors and other~~, causing problems~~, such as lowering the time resolution. Accordingly, a known ultrasonic transducer~~in a known technique, a proposal~~ has been proposed~~made~~

~~of an ultrasonic transducer~~ in which a setting is determined such that the acoustic characteristic impedance of the backing layer has substantially the same value as the acoustic characteristic impedance of the piezoelectric body constituting the piezoelectric resonator, and both of them are ~~bonded~~ integrally bonded (for example, see Japanese Unexamined ~~refer to~~ Patent Application Publication No. 2003-37896 (Patent Document 2)).

[0005] ———Incidentally, when applying a drive pulse to an ultrasonic transducer, the shape of the drive pulse is important.~~becomes an issue.~~ When a piezoelectric body is used in an ultrasonic transducer, the applied voltage pulse (= drive pulse) and the displacement have substantially the same waveform, and the sound pressure and the particle speed of the generated ultrasonic wave pulse has ~~comes to have~~ substantially the same waveform as the time differentiation of the applied voltage pulse. That is to say, when the drive pulse is a rectangular wave, the differentiation of a rise of a pulse becomes a peak that rises and falls~~one mountain rising and falling~~, whereas a fall of a pulse becomes a valley that falls and rises.~~falling and rising on the contrary.~~ In short, when a drive pulse having~~of~~ a rectangular shape is applied, a sound wave is generated by the differentiation value of the pulse. Thus, for example, an ultrasonic waveform having two consecutive changes, a peak~~mountain~~ and a valley, is generated as a waveform of $T_d = 350$ nsec in Fig. 5. In this regard, when the element is driven using, for example, a transistor, ~~etc.,~~ the drive current is limited,

and thus, the voltage across the terminals of the element ~~is becomes~~ a triangular wave rather than a rectangular wave if the electrostatic capacity thereof is large. This causes a ~~the~~ lowering of the sound pressure of the generated ultrasonic pulse, and thus, it is desirable to make the drive current as large as possible and to make the electrostatic capacity of the element as small as possible such that ~~in order to make~~ the voltage across the terminals is substantially ~~as near as~~ a rectangular wave at implementation time. When the pulse width is wide, the ~~peak~~ ~~mountain~~ and a valley are separated in time.

[0006] ——— On the other hand, when the sound speed in various liquids as described above is ~~are~~ measured, ~~the~~ measurements are made of the time required from applying a drive pulse shown in Fig. 23A ~~(a)~~ to an ultrasonic transducer to the receiving of the wave. At that time, for ~~from~~ example, as shown in Figs. 23B ~~(b)~~ and 23C ~~(c)~~, if the receiving side measures T1, which is the time period required for the wave to reach the vicinity of the peak of the ~~mountain~~ waveform or the valley ~~peak~~, the measurement is likely ~~liable~~ to be affected by the gain of an amplifier, noises, and other interference, etc., and thus, the measurement precision is likely ~~apt~~ to be deteriorated.

[0007] ——— Accordingly, up to now, as shown in Figs. 23D ~~(d)~~ and 23E ~~(e)~~, the detection has been carried out on T2, which is the time of crossing the point of a zero amplitude during a fall from a ~~peak~~ ~~mountain~~ toward the next valley, namely up to a zero-cross point.

~~Patent Document 1: Japanese Unexamined Patent Application
Publication No. 15-259490~~

~~Patent Document 2: Japanese Unexamined Patent Application
Publication No. 2003-37896~~

~~Disclosure of Invention~~

~~Problems to be Solved by the Invention~~

[0008] ——— In order to detect the zero-cross point of a received signal with high precision as described above, it is desirable that the gradient of the waveform at the zero-cross point is as sharp as possible. However, in a known technique, the waveform of the drive pulse to be applied to an ultrasonic transducer, particularly the pulse width, has not been fully examined. Thus, measurement errors increase. For example, the detection position ~~is becomes~~ unclear when the zero-cross point is detected. Accordingly, problems, such as the decrease of time resolution, ~~etc.,~~ have occurred.

[0009] ——— Also, when a setting is determined such that the acoustic characteristic impedance of the backing layer has substantially the same value as the acoustic characteristic impedance of the piezoelectric body ~~defining~~constituting the piezoelectric resonator as disclosed in Patent Document 2, it ~~is becomes~~ possible to suppress the reflection on the boundary surface of both of the layers to a certain extent.

[0010] ——— However, even in this ~~that~~ case, the reflection of an ultrasonic wave occurs on the end surface of the open side, which is the opposite side of the backing layer to the boundary

surface with the piezoelectric resonator, and thus, this reflection component is transmitted to the receiving side to cause measurement errors. Accordingly, it is necessary to prevent the influence of the reflection on the end surface of the open side of the backing layer.

SUMMARY OF THE INVENTION

[0011] To overcome the problems described above, preferred embodiments ~~The present invention has been made in view of the above-described problems. It is an object of the present invention to provide a method of driving an ultrasonic transducer capable of increasing the detection precision of the zero-cross point and improving the measurement precision of the ultrasonic wave as compared to known ultrasonic transducers~~ better than before without being influenced by the reflection on the end surface of the open side of the backing layer.

According to a preferred embodiment of the present invention,
~~Means for Solving the Problems~~

[0012] ~~In order to achieve the above-described object, according to the invention described in Claim 1, there is provided a method of driving an ultrasonic transducer having a piezoelectric resonator including~~ formed by a pair of electrodes sandwiching a piezoelectric body and provided with a backing layer in contact ~~contacting~~ with one of the electrodes of the piezoelectric resonator and having the same acoustic characteristic impedance as the piezoelectric body is provided,

the method including the step of driving the piezoelectric resonator so as to satisfy a condition:

$$2T_h \leq T_d \leq 6T_h$$

—where T_h is a propagation time of an ultrasonic wave in the piezoelectric body sandwiched by the pair of electrodes, and T_d is a pulse width of a drive pulse driving the piezoelectric resonator.

[0013] In the ~~—The method of driving an ultrasonic transducer~~ according to this preferred embodiment~~the invention described in Claim 2 is,~~ in the method of driving described in Claim 1, a setting is preferably determined so as to satisfy a condition:

$$T_d < (2L_2 + L_1)/V$$

—where L_1 is a thickness of the piezoelectric body sandwiched by the pair of electrodes, L_2 is a thickness of the backing layer, and V is a sound speed when an ultrasonic wave propagates in the piezoelectric body and the backing layer.

[0014] In the ~~—The method of driving an ultrasonic transducer~~ according to this preferred embodiment~~the invention described in Claim 3 is,~~ in the method of driving described in Claim 1 or Claim 2, when a pair of the ultrasonic transducers are disposed opposite to each other and~~with~~ sandwiching a substance to define~~be~~ an ultrasonic transmission target, a setting is preferably determined so as to satisfy a condition:

$$(R^2 + X^2)^{1/2} - X > (VM \times T_d)$$

where X is a distance between both of the opposite ultrasonic transducers, $2R$ is a length of a short side or a

diameter of an ultrasonic wave emission surface, V_M is a sound speed of an ultrasonic wave propagating in the substance, and λ is a wavelength of the ultrasonic wave propagating in the substance, represented by $\lambda = (V_M \times T_d)$.

[0015] In the ~~—The~~ method of driving an ultrasonic transducer according to this preferred embodiment~~the invention described in Claim 4 is, in the method of driving described in any one of claims 1 to 3,~~ when there is a partition wall made of a substance different from a substance of an ultrasonic wave emission surface of the piezoelectric resonator and a substance to be a target of ultrasonic transmission therebetween, a setting is preferably determined so as to satisfy a condition:

$$T_d < 2L_w/V_w$$

~~—~~where L_w is a thickness of the partition wall, and V_w is a sound speed when an ultrasonic wave propagates in the partition wall.

[0016] In the ~~—The~~ method of driving an ultrasonic transducer according to this preferred embodiment~~the invention described in Claim 5 is, in the method of driving described in Claim 4,~~ a setting is preferably determined such that an acoustic characteristic impedance has a value between an acoustic characteristic impedance of the piezoelectric resonator and an acoustic characteristic impedance of the substance to be a target of ultrasonic transmission.

With Advantages

[0017] ~~—By~~ the method of driving an ultrasonic transducer

according to various preferred embodiments of the present invention~~described in Claim 1~~, the pulse width of the drive pulse is set to satisfy a desired~~certain~~ condition at the transmission side, and thus,~~it is possible to keep~~ the slope of the waveform at the zero-cross point is sharp at the receiving side. Thus,~~it is possible to increase~~ the detection precision of the zero-cross point is increased. Accordingly, the time resolution improves as compared to~~better than before~~ when an ultrasonic wave is received, and thereby ~~it becomes possible to measure~~ sound speed can be measured with high precision.

[0018] The ~~By the method of driving an ultrasonic transducer according to the invention described in Claim 2~~, the pulse width of the drive pulse or the thickness of the backing layer is set to satisfy a desired~~certain~~ condition at the transmission side, and thus,~~the receiving side is not influenced by the reflection on the end surface of the open side of the backing layer at an ultrasonic-wave transmission time.~~ Accordingly, ~~it becomes possible to improve the measurement precision of the ultrasonic wave~~ is improved~~better than before~~.

[0019] In addition ~~By the method of driving an ultrasonic transducer according to the invention described in Claim 3~~, the distance X between the pair of ultrasonic transducers is set to satisfy a desired~~certain~~ condition, and thus,~~the ultrasonic wave is received in a near acoustic field.~~ Accordingly, ~~it is possible to eliminate the influence of a diffracted wave~~ is eliminated, and thus,~~it becomes possible to improve the~~

measurement precision of the ultrasonic wave is improved~~better~~
~~than before.~~

[0020] When ~~By the method of driving an ultrasonic~~
~~transducer according to the invention described in Claim 4,~~ when
there is a partition wall made of a substance different from a
substance of an ultrasonic wave emission surface of the
piezoelectric resonator and a substance to be a target of
ultrasonic transmission therebetween, the pulse width of the
drive pulse or the thickness of the partition wall is set to
satisfy a desired~~certain~~ condition, and thus, ~~it is possible for~~
the receiving side eliminate~~to eliminate~~ the influence of the
reflection caused on the partition wall. Accordingly, the time
resolution improves ~~better than before~~ when an ultrasonic wave is
received, and thereby ~~it becomes possible to measure~~ sound speed
is measured with high precision.

[0021] Furthermore ~~By the method of driving an ultrasonic~~
~~transducer according to the invention described in Claim 5,~~ an
acoustic characteristic impedance has a value between an acoustic
characteristic impedance of the piezoelectric resonator and an
acoustic characteristic impedance of the substance to be a target
of ultrasonic transmission, and thus the amount of attenuation by
the reflection of the ultrasonic wave on the partition wall is
reduced~~can be made small~~. Accordingly, an ultrasonic wave is~~it~~
~~is possible to~~ efficiently transmitted ~~transmit an ultrasonic~~
~~wave~~ toward the receiving side.

~~Best Mode for Carrying Out the Invention~~

[0022] —According to the preferred embodiments of the present invention, the method of driving an ultrasonic transducer has a piezoelectric resonator including~~formed by~~ a pair of electrodes sandwiching a piezoelectric body and provided with a backing layer in contacting with one of the electrodes of the piezoelectric resonator and having the same acoustic characteristic impedance as the piezoelectric body, the method including the step of driving the piezoelectric resonator so as to satisfy a condition:

$$2T_h \leq T_d \leq 6T_h \quad (1)$$

—where T_h is a propagation time of an ultrasonic wave in the piezoelectric body sandwiched by the pair of electrodes, and T_d is a pulse width of a drive pulse driving the piezoelectric resonator.

[0023] —When measuring sound speeds in various liquids, it is preferable to have the gradient of the waveform at the zero-cross point as sharp as possible in order to detect the zero-cross point of the signal of the received wave with high precision. That is to say, when the pulse width T_d of the drive pulse is too wide, the gradient of the waveform at the zero-cross point is reduced~~becomes moderate~~, and thus, the zero-cross point becomes unclear. Also, when the pulse width T_d is extremely narrow, the signal level is reduced~~becomes low~~, and thus, the S/N ratio is deteriorated. In addition, the degree of change from a peak~~mountain~~ to a valley is reduced~~becomes small~~, and thus, the gradient of the waveform at the zero-cross point is

~~reduced~~~~becomes moderate~~, resulting in an unclear zero-cross point. In contrast, when the pulse width T_d of the drive pulse is set so as to satisfy the above-described condition (1), ~~it is possible to make~~ the gradient of the waveform at the zero-cross point is sharp. Accordingly, ~~it is possible to increase~~ the detection precision of the zero-cross point is increased, and thus, ~~it is possible to increase~~ the measurement precision of the ultrasonic wave is improved~~better than before~~.

[0024] —Also, in the method of driving an ultrasonic transducer according to preferred embodiments of the present invention, when using~~employing~~ the above-described driving method, a setting is determined so as to satisfy a condition:

$$T_d < (2L_2 + L_1)/V \quad (2)$$

—where L_1 is a thickness of the piezoelectric body sandwiched by the pair of electrodes, L_2 is a thickness of the backing layer, and V is a sound speed when an ultrasonic wave propagates in the piezoelectric body and the backing layer.

[0025] —If the thickness L_2 of the backing layer is set to satisfy the above-described condition (2) in advance, ~~it is possible to separate in time~~ the ultrasonic wave directly generated from the piezoelectric resonator can be separated in time from ~~and~~ the ultrasonic wave reflected on the end surface of the open side of the backing layer. Accordingly, ~~it is possible to eliminate~~ the influence of the ultrasonic wave reflected on the end surface of the open side of the backing layer is eliminated, and thus, ~~it is possible to improve~~ the measurement

precision of the ultrasonic wave is improved.~~better than before.~~

In this regard, the pulse width T_d of the drive pulse may be set to satisfy the above-described condition (2) in place of setting the thickness L_2 of the backing layer. When ~~In this regard,~~ when an ultrasonic transducer having the same structure as the transmitter is used as a receiver, the receiver should be set to satisfy the condition (2).

[0026] —Furthermore, in the method of driving an ultrasonic transducer according to preferred embodiments of the present invention, when a pair of ultrasonic transducers are disposed to sandwich~~opposite with sandwiching~~ a substance to be an ultrasonic transmission target, a setting is determined so as to satisfy a condition:

$$(R^2 + X^2)^{1/2} - X > (V_M \times T_d) \quad (3)$$

—where X is a distance between both of the opposite ultrasonic transducers, $2R$ is a length of a short side or a diameter of an ultrasonic wave emission surface, V_M is a sound speed of an ultrasonic wave propagating in the substance, and λ is a wavelength of the ultrasonic wave propagating in the substance, represented by $\lambda = (V_M \times T_d)$.

[0027] —That is to say, the ultrasonic wave to be transmitted includes direct waves simultaneously emitted from substantially~~all over~~ the entire transmission surface and the diffracted wave having reverse polarity emitted from the edge portion of the transmission surface. However, when the distance X between the pair of the ultrasonic transducers is set to

satisfy the above-described condition (3), the ultrasonic wave is received in a near acoustic field, and thus, it is possible to separate and eliminate the influence of the diffracted wave in time. Accordingly, ~~it becomes possible to improve the~~ measurement precision of the ultrasonic wave is improved.

~~_____ better than before.~~

[0028] ~~_____~~ Moreover, ~~in the method of driving an ultrasonic transducer according to the present invention,~~ when there is a partition wall made of a substance different from a substance of the ultrasonic wave emission surface of the piezoelectric resonator and a substance to be a target of ultrasonic transmission therebetween, a setting is determined so as to satisfy a condition:

$$T_d < 2L_w/V_w \quad (4)$$

~~_____~~ where L_w is a thickness of the partition wall, and V_w is a sound speed when an ultrasonic wave propagates in the partition wall.

[0029] ~~_____~~ If the thickness L_w of the partition wall is set to satisfy the above-described condition (4), ~~it is possible to eliminate the influence of the reflection caused on the partition wall at the receiving side~~ is eliminated. That is to say, ~~it is possible to separate in time the ultrasonic wave directly generated from the piezoelectric resonator~~ is separated in time from ~~and the ultrasonic wave reflected on the end surface of the partition wall.~~ Accordingly, the time resolution improves ~~better than before~~ when an ultrasonic wave is received, and thereby, ~~it~~

~~becomes possible to measure a sound speed~~ can be measured with high precision. In this regard, the pulse width T_d of the drive pulse may be set to satisfy the above-described condition (4) in place of setting the thickness L_w of the partition wall.

[0030] ~~Also, in the method of driving an ultrasonic transducer according to the present invention,~~ a setting is determined such that an acoustic characteristic impedance of the partition wall has a value between an acoustic characteristic impedance of the piezoelectric resonator and an acoustic characteristic impedance of the substance to be a target of ultrasonic transmission. Thus, the amount of attenuation by the reflection of the ultrasonic wave on the partition wall can be reduced. ~~made small.~~ Accordingly, ~~it is possible to efficiently transmit~~ an ultrasonic wave is efficiently transmitted toward the receiving side. As a matter of course, when an ultrasonic transducer having the same structure as the transmitter is used as a receiver, it is preferable to set the thickness L_w of the partition wall and the acoustic characteristic impedance as described above.

[0031] Other features, elements, steps, characteristics and advantages of the present invention will become more apparent from the following detailed description of preferred embodiments of the present invention with reference to the attached drawings.

~~Brief Description of the Drawings~~ BRIEF DESCRIPTION OF THE DRAWINGS

[0032] Figs. 1A and 1B illustrate ~~Fig. 1 illustrates~~ the configuration of an ultrasonic transducer in a ~~this~~ first preferred embodiment of the present invention. Fig. 1A~~(a)~~ is a sectional view, and Fig. 1B~~(b)~~ is a sectional view taken along line Z-Z of Fig. 1A.

[0033] Figs. 2A and 2B are 1(a). ~~Fig. 2 is a~~ planar sectional views ~~view~~ illustrating the specific size and shape of the electrode of the ultrasonic transducer shown in Fig. 1.

[0034] Fig. 3 is a configuration diagram of an apparatus used for observing the received waveform of the ultrasonic wave transmitted from the ~~this~~ ultrasonic transducer having the configuration shown in Figs. 1A and 1B.

[0035] Fig. 4 is an explanatory diagram in the case of applying a drive pulse of the ultrasonic transducer using the same apparatus.

[0036] Fig. 5 is a diagram showing the received waveform of the ultrasonic wave obtained when the pulse width of the drive pulse of the ultrasonic transducer is changed using the apparatus shown in Fig. 3.

[0037] Fig. 6 is a characteristic diagram showing the results of the measurement of each sound pressure of a peak and a valley of the received waveform of the ultrasonic wave obtained when the pulse width of the drive pulse of the ultrasonic transducer is changed using the apparatus shown in Fig. 3.

[0038] Fig. 7 is an explanatory diagram illustrating a relationship between the ultrasonic wave directly emitted from

the emission surface of the piezoelectric resonator and the ultrasonic wave emitted by being reflected from the open end surface of the backing layer and passing through the piezoelectric resonator 2—again in the ultrasonic transducer having the configuration shown in Figs. 1A and 1B.

[0039] Figs. 8A and 8B are explanatory diagrams illustrating the comparison between the drive pulse applied to the ultrasonic transducer and the waveform of the received ultrasonic wave.

0040] Fig. 9 is an explanatory diagram in the case of configuring an ultrasonic transmitter/receiver by placing opposite a pair of ultrasonic transducers driven with the configuration and the condition described in a first preferred embodiment and a second preferred embodiment of the present invention at a predetermined distance.

[0041] Fig. 10 is an explanatory diagram in the case of configuring another ultrasonic transmitter/receiver by placing opposite a pair of ultrasonic transducers driven with the configuration and the condition described in a first preferred embodiment and a second preferred embodiment of the present invention at a predetermined distance.

[0042] Fig. 11 is an explanatory diagram in the case of setting an opposed distance in order to separate the direct wave and the diffracted wave generated with ultrasonic emission in the ultrasonic transmitter/receiver shown in Fig. 9 or Fig. 10.

[0043] Figs. 12A and 12B are characteristic diagrams showing the received waveform generated when the opposed distance between

a pair of ultrasonic transducers in Fig. 11 is changed.

[0044] Fig. 13 is a graph plotting $\Delta = \{\sqrt{(R^2 + X^2)}\} - X$ using the length of the short side or the diameter $2R$ of the ultrasonic wave transmission surface as a parameter.

[0045] Fig. 14 is a characteristic diagram showing the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water temperature, using the ultrasonic transmitter/receiver having the configuration shown in Fig. 9.

[0046] Figs. 15A and 15B are characteristic diagrams showing the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water temperature, using the ultrasonic transmitter/receiver having the configuration shown in Fig. 10.

[0047] Fig. 16 is an explanatory diagram schematically illustrating the situation in the case where there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.

[0048] Figs. 17A and 17B are characteristic diagrams showing a result obtained by measuring the propagation situation of the ultrasonic wave depending on the existence of a partition wall using the ultrasonic transmitter/receiver having the configuration shown in Fig. 9.

[0049] Fig. 18 is an explanatory diagram schematically illustrating the situation in the case where an ultrasonic wave is reflected by the existence of the partition wall when there is a partition wall between a pair of ultrasonic transducers and a

substance to be measured.

[0050] Figs. 19A and 19B are characteristic diagrams showing the result obtained by measuring the propagation situation of the ultrasonic wave with partition walls having different thicknesses when there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.

[0051] Figs. 20A and 20B are characteristic diagrams showing the result obtained by measuring the propagation situation of the ultrasonic wave in accordance with the difference of the material of a partition wall using the ultrasonic transmitter/receiver having the configuration shown in Fig. 9.

[0052] Fig. 21 is an explanatory diagram showing relationships among the density, the sound speed, and the acoustic characteristic impedance of various materials.

[0053] Figs. 22A-22C illustrate a flow tube to be applied when the ultrasonic transmitter/receiver shown in Fig. 9 or Fig. 10 is used. Fig. 22A is a partially cutaway front view showing the state in which the ultrasonic transmitter/receiver is attached, Fig. 22B is a side view thereof, and Fig. 22C is a sectional view taken along line Y-Y of Fig. 22A.

[0054] Figs. 23A-23E are timing charts showing relationships among a drive pulse, received ultrasonic waveforms, and measurement pulses when the sound speed in a substance is measured using the ultrasonic transducer.

[0055] Figs. 24A-24C are waveform charts to be used for an explanation for setting an optimum range of the pulse width of a

drive pulse in a method of driving an ultrasonic transducer according to a preferred embodiment of the present invention.

[0056] Figs. 25A and 25B are waveform charts to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in the method of driving the ultrasonic transducer according to a preferred embodiment of the present invention.

[0057] Figs. 26A-26C are waveform charts to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in the method of driving the ultrasonic transducer according to a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0058] In the following, a description will be given of specific preferred embodiments of the method of driving an ultrasonic transducer. ~~In the following, a description will be given of specific embodiments which become a basis of employing the above-described method of driving an ultrasonic transducer.~~

First Preferred Embodiment

[0059] Figs. 1A and 1B illustrate the configuration of an ultrasonic transducer in a first preferred embodiment of the present invention. Fig. 1A is a sectional view, and Fig. 1B is a sectional view taken along line Z-Z of Fig. 1A. Figs. 2A and 2B are planar sectional views illustrating the specific size and shape of the electrode of this ultrasonic transducer.

[0060] The ultrasonic transducer 1 of this first preferred embodiment includes a piezoelectric body 3 preferably made of a ceramic material, such as a lead zirconate titanate (PZT) or other suitable ceramic material, and a pair of electrodes 4 and 5 are disposed in the piezoelectric body 3 with a predetermined distance therebetween. The portion of the piezoelectric body 3 sandwiched by the pair of electrodes 4 and 5 is subjected to polarization processing to define a piezoelectric active portion 31. Thus, a piezoelectric resonator 2 is defined by this piezoelectric active portion 31 and the pair of electrodes 4 and 5.

[0061] Furthermore, the portion of the piezoelectric body located outside of the electrode 5 of the piezoelectric resonator 2 includes ~~— The ultrasonic transducer 1 of this first embodiment includes a piezoelectric body 3 made of a ceramic material such as a lead zirconate titanate (PZT), etc., and a pair of electrodes 4 and 5 are formed in the piezoelectric body 3 with a predetermined distance. The portion of the piezoelectric body 3 sandwiched by the above-described pair of electrodes 4 and 5 is subjected to polarization processing to constitute a piezoelectric active portion 31. Thus, a piezoelectric resonator 2 is constituted by this piezoelectric active portion 31 and the pair of electrodes 4 and 5.~~

~~— Furthermore, the portion of the piezoelectric body located outside of one of electrodes 5 of this piezoelectric resonator 2 is formed as a backing layer 32. Also, the outside of the other~~

~~of electrodes 4 is provided with a thin outer layer 33. Accordingly, the piezoelectric active portion 31, the backing layer 32, and the outer layer 33, which constitute the piezoelectric resonator 2, are integrated together to have the same acoustic characteristic impedance. In this regard, the backing layer 32 and the outer layer 33 are non-polarized and in a non-active state, but may have been subjected to polarization processing. Also, external connection electrodes 7 and 8, which are individually connected to the lead-out portions 4a and 5a of the electrodes 4 and 5, respectively, are formed on the end face of the side perpendicular to the electrode-formed face of the piezoelectric resonator 2.~~

~~—— In this first embodiment, the ultrasonic transducer 1 having the above-described configuration is produced as follows. First, water and binder is added to piezoelectric ceramic powder whose main component is a lead zirconate titanate (PZT) to form a sheet. The thickness of this ceramic sheet per one layer is about 65 μm before sintering and about 40 μm after sintering. Silver-palladium paste is printed on the portion corresponding to the electrodes 4 and 5 by a screen printing method. The amount of palladium is selected in a range of 0 to 80% depending on a burning condition, etc. Here, the amount was determined to be 30%.~~

~~—— Using the above-described sheets, four layers of the ceramic sheets were laminated for forming the piezoelectric active portion 31, 37 layers were laminated for forming the backing~~

~~layer 32, and one layer was laminated for forming the outer layer. The sheets were integrally burned at a temperature up to a maximum of about 100° C. The entire dimensions of the ultrasonic transducer 1 were 6 × 9 × 1.7 mm after burning. At that time, the thickness of the piezoelectric active portion 31 was about 160 μm, the thickness of the backing layer 32 was about 1.5 mm, and the thickness of the outer layer 33 was about 40 μm. Also, as shown in Fig. 2, the thickness of each of the electrodes 4 and 5 is 1 to 2 μm, the size of the portion of each of the electrodes 4 and 5, which is opposed to the piezoelectric active portion 31, is a 5.5-mm square, and the width of the lead-out portions 4a and 5a is 0.5 mm. The lead-out portions 4a and 5a are shifted with each other in order not to have piezoelectric activity.~~

~~—— Next, in order to electrically connect each of the electrodes 4 and 5 and the outside, external connection electrodes 6 and 7 were formed on the exposed portion to the side face of the lead-out portions 4a and 5a of the electrodes 4 and 5. The external connection electrodes 6 and 7 were formed by applying electrode paste made of silver powder and glass powder and burning at a temperature of about 800°C. In this regard, a metal film can be formed by a method using a vacuum technique such as deposition and sputtering. Next, polarization processing was performed by applying a direct current of 480 V across both of the external connection electrodes 6 and 7.~~

~~—— The ultrasonic transducer 1 created in this manner was disposed in a water tank 10 as shown in Fig. 3. The ultrasonic~~

~~wave emitted from the ultrasonic transducer 1 was received by a PVDF hydrophone 11, and the received waveform was observed by a digital oscilloscope 13 through a pre-amplifier 12. The driving of the ultrasonic transducer 1 was carried out by generating a single-shot pulse having various pulse widths by a pulse generator 14 and applying this pulse to the ultrasonic transducer 1 through a driver 15. That is to say, as shown in Fig. 4, a single-shot pulse is directly applied to one of the electrodes 4 through an amplifier 15a using an inverter of the driver 15. Also, the pulse amplified by the amplifier 15a is level-inverted through an inverter 15b, and then is applied to the other of the electrodes 5. In this regard, the basic operation is the same in the case of using only one inverter rather than using two inverters. That is to say, in the present invention, the control of the pulse width is important regardless of the driving method.~~

~~Fig. 5 shows the waveforms observed at the propagation distance $X = 5$ mm when ultrasonic waves were transmitted by applying a single-shot pulse having various pulse widths T_d across both electrodes of the ultrasonic transducer 1. Also, Fig. 6 is measured results of individual sound pressures of a mountain peak and a valley peak of the received waveform when the pulse width T_d of the drive pulse is changed.~~

~~As is understood from these figures, when the pulse width T_d is in a small range less than 80 nsec, each amplitude of a mountain and a valley is also small, the degree of change is mild, the waveforms of a mountain and a valley are asymmetric, and thus~~

~~the zero-cross point is not clear. Also, when the pulse width T_d is larger than 250 nsec, a mountain and a valley of the waveform of an ultrasonic wave is separated, the slope of the waveform at the zero-cross point becomes mild, and thus the detection point at the time of detecting the zero-cross point becomes unclear.~~

~~—— In contrast, when the pulse width T_d is between 80 nsec and 250 nsec, the symmetry of a mountain and a valley of an ultrasonic waveform is good, and the gradient of the waveform at the zero-cross point changing from a mountain to a valley is relatively sharp. Thus, it is possible to detect the zero-cross point with high precision.~~

~~—— In the case of the first embodiment, the thickness of the piezoelectric active portion 31 constituting the piezoelectric resonator 2 is about 160 μm , the sound speed at that time is about 4000 m/s, and thus the propagation time T_h of the piezoelectric active portion 31 is about 40 nsec. The detection precision of the zero-cross point is high when the pulse width T_d is between 80 nsec and 250 nsec as described above. Thus, when specifying the pulse width T_d by the propagation time T_h , it is understood that the zero-cross point can be detected clearly if the pulse width T_d of the drive pulse is set in a range of two to six times the propagation time T_h of an ultrasonic wave passing the piezoelectric active portion 32. Accordingly, if the driving is carried out by setting the pulse width T_d of the drive pulse to satisfy $2 \leq (T_d/T_h) \leq 6$, namely the above-described condition (1), it is possible to clearly detect the zero-cross point.~~

~~Moreover, the optimum range for clearly detecting the zero-cross point is $2 \leq (T_d/T_h) \leq 3$. The reason for this will be described with reference to Figs. 24 to 26.~~

~~First, an ideal case is considered. When a drive pulse (a pulse width T_d) shown in Fig. 24(a) is applied to the ultrasonic transducer 1, the displacement waveform at that time becomes as shown in the same figure (b). Also, at this time, the waveform of the sound pressure generated from the ultrasonic transducer 1 becomes as shown in the same figure (c). In this case, assuming that the displacement waveform needs the time T_h at a rise and a fall of the drive pulse, individually, the width of the mountain and the width of the valley of the sound waveform become the same T_h . In order to have good symmetry in the mountain and the valley of the ultrasonic waveform and a sharp slope of the waveform at the zero-cross point, it is necessary that the time period between the mountain and the valley of the ultrasonic waveform $T_g \approx 0$. Accordingly, when $T_d = T_h$ as shown in Fig. 25(a)~~
backing layer 32. Also, the outside of the other electrode 4 is provided with a thin outer layer 33. Accordingly, the piezoelectric active portion 31, the backing layer 32, and the outer layer 33, which define the piezoelectric resonator 2, are integrated together to have the same acoustic characteristic impedance. In this regard, the backing layer 32 and the outer layer 33 are non-polarized and in a non-active state, but may have been subjected to polarization processing. Also, external connection electrodes 7 and 8, which are individually connected

to the lead-out portions 4a and 5a of the electrodes 4 and 5, respectively, are provided on the end surface of the side that is substantially perpendicular to the electrode-bearing surface of the piezoelectric resonator 2.

[0062] In this first preferred embodiment, the ultrasonic transducer 1 having the above-described configuration is produced as follows. First, water and binder are added to a piezoelectric ceramic powder whose main component is a lead zirconate titanate (PZT) to form a sheet. The thickness of one layer of this ceramic sheet is about 65 μm before sintering and about 40 μm after sintering, for example. Silver-palladium paste is printed on the portion corresponding to the electrodes 4 and 5 by a screen printing method. The amount of palladium is preferably in a range of about 0 to about 80% depending on a burning condition and other factors. Here, the amount was determined to be about 30%.

[0063] Using the above-described sheets, four layers of the ceramic sheets were laminated to form the piezoelectric active portion 31, 37 layers were laminated to form the backing layer 32, and one layer was laminated to form the outer layer. The sheets were integrally burned at a temperature up to a maximum of about 100° C. The entire dimensions of the ultrasonic transducer 1 were about 6 × 9 × 1.7 mm, for example, after burning. At this time, the thickness of the piezoelectric active portion 31 was about 160 μm , the thickness of the backing layer 32 was about 1.5 mm, and the thickness of the outer layer 33 was about 40 μm , for

example. Also, as shown in Fig. 2, the thickness of each of the electrodes 4 and 5 is about 1 μm to about 2 μm , the size of the portion of each of the electrodes 4 and 5, which is opposed to the piezoelectric active portion 31, is about 5.5-mm square, and the width of the lead-out portions 4a and 5a is about 0.5 mm. The lead-out portions 4a and 5a are shifted with respect to each other in order not to have piezoelectric activity.

[0064] Next, in order to electrically connect each of the electrodes 4 and 5 to the outside, external connection electrodes 6 and 7 were formed on the exposed portion to the side surface of the lead-out portions 4a and 5a of the electrodes 4 and 5. The external connection electrodes 6 and 7 were formed by applying electrode paste made of silver powder and glass powder and burning at a temperature of about 800°C. In this regard, a metal film can be formed by a method using a vacuum technique, such as deposition and sputtering. Next, polarization processing was performed by applying a direct current of about 480 V across both of the external connection electrodes 6 and 7.

[0065] The ultrasonic transducer 1 created in this manner was disposed in a water tank 10 as shown in Fig. 3. The ultrasonic wave emitted from the ultrasonic transducer 1 was received by a PVDF hydrophone 11, and the received waveform was observed by a digital oscilloscope 13 through a pre-amplifier 12. The driving of the ultrasonic transducer 1 was performed by generating a single-shot pulse having various pulse widths by a pulse generator 14 and applying this pulse to the ultrasonic transducer

1 through a driver 15. That is to say, as shown in Fig. 4, a single-shot pulse is directly applied to the electrode 4 through an amplifier 15a using an inverter of the driver 15. Also, the pulse amplified by the amplifier 15a is level-inverted through an inverter 15b, and then is applied to the electrode 5. In this regard, the basic operation is the same in the case of using only one inverter rather than using two inverters. That is to say, in the present invention, the control of the pulse width is important regardless of the driving method.

[0066] Fig. 5 shows the waveforms observed at the propagation distance $X = 5$ mm when ultrasonic waves were transmitted by applying a single-shot pulse having various pulse widths T_d across both electrodes 4 and 5 of the ultrasonic transducer 1. Also, Fig. 6 shows measured results of individual sound pressures of a peak and a valley of the received waveform when the pulse width T_d of the drive pulse is changed.

[0067] As understood from these figures, when the pulse width T_d is in a small range of less than about 80 nsec, each amplitude of a peak and a valley is also small, the degree of change is mild, the waveforms of a peak and a valley are asymmetric, and thus the zero-cross point is not clear. Also, when the pulse width T_d is larger than about 250 nsec, a peak and a valley of the waveform of an ultrasonic wave is separated, the slope of the waveform at the zero-cross point is mild, and thus the detection point at the time of detecting the zero-cross point is unclear.

0068] In contrast, when the pulse width T_d is between about

80 nsec and about 250 nsec, the symmetry of a peak and a valley of an ultrasonic waveform is greatly improved, and the gradient of the waveform at the zero-cross point changing from a peak to a valley is relatively sharp. Thus, the zero-cross point can be detected with high precision.

[0069] In the first preferred embodiment, the thickness of the piezoelectric active portion 31 defining the piezoelectric resonator 2 is about 160 μm , the sound speed at that time is about 4,000 m/s, and thus, the propagation time T_h of the piezoelectric active portion 31 is about 40 nsec. The detection precision of the zero-cross point is greatly improved when the pulse width T_d is between about 80 nsec and about 250 nsec as described above. Thus, when specifying the pulse width T_d by the propagation time T_h , it is understood that the zero-cross point can be detected clearly if the pulse width T_d of the drive pulse is set in a range of about two times to about six times the propagation time T_h of an ultrasonic wave passing the piezoelectric active portion 32. Accordingly, if the driving is performed by setting the pulse width T_d of the drive pulse to satisfy $2 \leq (T_d/T_h) \leq 6$, namely the above-described condition (1), the zero-cross point can be clearly detected.

[0070] Moreover, the optimum range for clearly detecting the zero-cross point is $2 \leq (T_d/T_h) \leq 3$. The reason for this will be described with reference to Figs. 24 to 26.

[071] First, an ideal case is considered. When a drive pulse (a pulse width T_d) shown in Fig. 24A is applied to the ultrasonic

transducer 1, the displacement waveform at that time becomes as shown in Fig. 24B. Also, at this time, the waveform of the sound pressure generated from the ultrasonic transducer 1 becomes as shown in Fig. 24C. In this case, assuming that the displacement waveform requires the time T_h at a rise and a fall of the drive pulse, individually, the width of the peak and the width of the valley of the sound waveform become the same T_h . In order to have good symmetry in the peak and the valley of the ultrasonic waveform and a sharp slope of the waveform at the zero-cross point, it is required that the time period between the peak and the valley of the ultrasonic waveform $T_g \approx 0$. Accordingly, when $T_d = T_h$ as shown in Fig. 25A, the optimum ultrasonic waveform is obtained as shown in Fig. 25B~~the same figure (b)~~.

[072] _____ However, the actual drive pulse has a waveform similar to~~just like~~ a waveform of discharging an electrical charge charged in a capacitor through a resistor as shown in Fig. 26A~~(a)~~, and thus, the displacement waveform of the ultrasonic transducer 1 requires~~needs~~ $T_r + T_h$ as the time from the start of the application of the drive pulse to the piezoelectric body 3 to the end as shown in 26B~~the same figure (b)~~ in view~~consideration~~ of the rise time T_r of the signal. Thus, the waveform of the sound wave generated from the ultrasonic transducer 1 becomes the one as shown in Fig. 26C~~the same figure (c)~~. Also, in this case, in order to have a sharp slope of the waveform at the zero-cross point, it is required~~necessary~~ that the time period between the mountain and the valley of the ultrasonic waveform $T_g \approx 0$.

Accordingly, the optimum ultrasonic waveform is ~~virtually~~ obtained when

$$T_d = T_r + T_h. \quad (I)$$

[073] ——— However, the rise time T_r of the signal shown in Figs. 26A-26C ~~depend~~. ~~26 depends~~ on the actual use condition, the circuit configuration, and other factors.~~etc.~~ The condition for obtaining the maximum voltage by the minimum electric current source is at the time of $T_h = T_r$. When applying this condition to the above-described expression (I), the result becomes $T_d = 2T_h$, namely $T_d/T_h = 2$. In reality, T_r becomes somewhat larger than T_h , and thus $T_d/T_h = 2$ shows the lower limit of the optimum range for detecting the zero-cross point clearly.

[074] ——— On the other hand, the upper limit of the optimum range for clearly detecting the zero-cross point depends on the value of T_r . The result of the experiment shown in Fig. 5 indicates that $T_d/T_h = 6$ (namely, $T_d = 250$ nsec) is the upper limit. However, as determined ~~is read out~~ from Fig. 5, when $T_d/T_h = 6$, the peak~~mountain~~ and the valley of the ultrasonic waveform are somewhat separated, and thus, the zero-cross point becomes somewhat~~rather~~ unclear. Accordingly, the result of the experiment shown in Fig. 5 indicates that $T_d/T_h = 3$ (namely, $T_d = 120$ nsec) is more desirable.

Second Preferred Embodiment~~embodiment~~

[075] ——— Fig. 7 shows the relationship between the ultrasonic wave directly emitted from the emission surface of the

piezoelectric resonator 2 and the ultrasonic wave reflected from the open-end surface 32a of the backing layer 32 and passing through the piezoelectric resonator 2 again to be emitted in the ultrasonic transducer 1 having the configuration shown in Fig. 1. Also, Figs. 8A and 8B show. ~~8 shows~~ the comparison between the drive pulse to be added to the ultrasonic transducer 1 and the waveform of the ultrasonic wave at the receiving time.

[076] ——— In the waveform at the time of receiving an ultrasonic wave, the time from the point of a rise of a peak ~~mountain~~ to the zero-cross point is substantially equal to the pulse width T_d of the drive pulse. Accordingly, if the time T_e , which is required for the ultrasonic wave generated by the piezoelectric resonator 2 to return to the emission surface of the piezoelectric resonator 2 again by being reflected from the open-end surface 32a of the backing layer 32, is greater ~~larger~~ than the pulse width T_d of the drive pulse ($T_e > T_d$), ~~it is possible to separate in time~~ the ultrasonic wave directly emitted from the emission surface of the piezoelectric resonator 2 can be separated from ~~and~~ the ultrasonic wave reflected from the open-end surface 32a of the backing layer 32 at the receiving side.

[077] ——— Here, assuming that L_1 is a thickness of piezoelectric active layer 31, L_2 is a thickness of the backing layer 32, and V is a sound speed when an ultrasonic wave propagates in the piezoelectric active layer 31 and the backing layer 32, $T_e = (2L_2 + L_1)/V$. Accordingly, if the thickness L_2 of the backing layer 32 is set to satisfy $(2L_2 + L_1)/V > T_d$, that is

to say, the above-described condition (2) in advance, ~~it is possible to eliminate~~ the influence of the ultrasonic wave reflected on the end surface of the open side of the backing layer 32 is eliminated. In this regard, the pulse width T_d of the drive pulse may be set to satisfy the above-described condition (2) in place of setting the thickness L_2 of the backing layer.

Third Preferred Embodiment~~embodiment~~

[078] ——— Fig. 9 and Fig. 10 are explanatory diagrams when a pair of ultrasonic transducers, which are driven with the configuration and the condition described in the first preferred embodiment and the second preferred embodiment, ~~embodiments~~, are disposed opposite at a predetermined distance to define~~constitute~~ an ultrasonic wave transmitter/receiver.

[079] ——— The ultrasonic wave transmitter/receiver 20 shown in Fig. 9 is produced by forming two pairs of opposed electrodes 4a and 5a, and 4b and 5b in the piezoelectric body 3 and cutting away the central portion located between each pair of the upper and the lower electrodes 4a and 5a, and 4b and 5b into a U-shape by a cutting process, ~~etc.~~ Thus, the ultrasonic wave transmitter/receiver 20 has a configuration in which a pair of ultrasonic transducers 1a and 1b having the same structure as the one shown in Fig. 1 are concatenated through a supporting member 34.

[080] ——— Accordingly, a pair of electrodes 4a and 5a

located in the upper ~~portion~~~~part~~ and the piezoelectric body sandwiched by these electrodes 4a and 5a, that is to say, the piezoelectric active portion 31a ~~defines~~~~constitute~~ a piezoelectric resonator 2a, and a backing layer 32a is formed on the back side of one of the electrodes 5a to ~~define~~~~constitute~~ one of ultrasonic transducers 2a. Similarly, a pair of electrodes 4b and 5b located in the lower ~~portion~~~~part~~ and the piezoelectric body sandwiched by these electrodes 4b and 5b, that is to say, the piezoelectric active portion 31b ~~defines~~~~constitute~~ a piezoelectric resonator 2b, and a backing layer 32b is formed on the back side of one of the electrodes 5b to ~~define~~~~constitute~~ one of the ultrasonic transducers 2b. The ultrasonic wave transmitter/receiver 20 having this configuration has advantages in that it ~~requires~~~~needs~~ only a few production man-hours, and it is easy to align both of the ultrasonic transducers 1a and 1b.

[081] ———The ultrasonic wave transmitter/receiver 21 shown in Fig. 10 is produced by bonding a pair of ultrasonic transducers 1a and 1b having substantially the same structure as the one shown in Fig. 1, respectively, using a spacer 22 and adhesive in a U-shape.

[082] ———Here, in the ultrasonic wave transmitters/receivers 20 and 21 shown in Fig. 9 or Fig. 10, the ~~opposed~~ distance X between the ultrasonic wave emission surfaces of a pair of ultrasonic transducers 1a and 1b is ~~preferably~~~~desirably~~ set as follows.

[083] ———As ~~Now, as~~ shown in Fig. 11, assuming that an

ultrasonic wave is transmitted from one ultrasonic transducer 1b ~~of~~ (for example, an upper ~~lower~~ side) ~~ultrasonic transducers 1b~~ toward the other ~~of~~ (here, an upper ~~lower~~ side) ~~ultrasonic transducers~~ 1a (here, an upper ~~lower~~ side), the ultrasonic waves to be transmitted include a direct wave emitted from ~~above~~ the transmission surface of the lower-side ultrasonic transducers 1b and a diffracted wave having reverse polarity emitted from the edge portion of the transmission surface.

[084] ——— When the direct wave and the diffracted wave arrive at ~~reach~~ the ultrasonic transducer 1a of the receiving side without overlapping, the zero-cross point from a peak ~~mountain~~ to a valley of the received waveform is clear as shown in Fig.

12A. ~~(a).~~ However, when the direct wave and the diffracted wave arrive at ~~reach~~ the ultrasonic transducer 1a of the receiving side in an ~~with~~ overlapping manner, as shown in Fig. 12B. ~~(b).~~, there are two zero-cross points, from a peak ~~mountain~~ to a valley and from a valley to a peak ~~mountain~~, of the received waveform before and after in a row, and thus, it is difficult to detect the zero-cross point with high precision. Accordingly, this results in deterioration of the time resolution at the time of receiving an ultrasonic wave.

[085] ——— Here, assuming that X is a ~~an~~ opposed distance on an acoustic axis 23 connecting a center of the ultrasonic wave surface of the lower-side ultrasonic transducer 1b and a center of the ultrasonic wave surface of the upper-side ultrasonic transducer 1a, 2R is a length (a diameter when the electrode 4b

is a circle) of a short side of the electrode 4b of the ultrasonic-wave emission surface, V_M is a sound speed of a ultrasonic wave propagating in the substance sandwiched by the upper and lower ultrasonic transducers 1a and 1b, a wavelength λ of the ultrasonic wave propagating in the substance is represented by $\lambda = V_M \times T_d$. A distance from the edge of the ultrasonic wave surface of one of the ultrasonic transducers 1b to the acoustic axis 23 of the ultrasonic wave surface of the other of the ultrasonic transducers 1a is represented by $(R^2 + X^2)^{1/2}$.

[086]——Now, when an ultrasonic wave emitted from the center of the ultrasonic wave surface of the lower-side ultrasonic transducer 1b travels the distance X and reaches the upper-side ultrasonic transducer 1a, the diffracted wave emitted from the edge also travels the same distance X . In order to separate the direct wave and the diffracted wave in time, it is necessary that the difference of distance $\Delta = (R^2 + X^2)^{1/2} - X$ between the direct wave and the diffracted wave at the time of the direct wave reaching the receiving side of the ultrasonic transducer 1a is more than the $V_M \times T_d$ ~~apart~~, which is the product of the sound speed V_M of a ultrasonic wave propagating in the substance and the pulse width T_d of the pulse.

[087]——Accordingly, if the opposed distance X is set to satisfy $\Delta > \lambda$, that is to say, the above-described condition (3), ~~it is possible to separate~~ the direct wave and the diffracted wave are separated in time, and ~~to detect~~ the zero-cross point

can be detected with high precision. In this regard, ~~in this case,~~ it is desirable for the above-described difference of the distance Δ to have a value substantially greater ~~as larger as possible~~ than the wavelength λ . That is to say, it is desirable to be in a near acoustic field. If Δ is too small (that is to say, the opposed distance X is large and in a far acoustic field), the direct wave and the diffracted wave cannot be separated. In this regard, if the ultrasonic transducer of the receiving side is large, the waves are received even when the direct wave and the diffracted wave cannot be separated. However, the direct wave enters with the same phase on ~~all over~~ the receiving wave surface, whereas the diffracted wave enters with different phases continuously. Thus, the influence of the diffracted wave ~~as a result~~ becomes very small.

[088] ——— Fig. 13 is a graph plotting $\lambda = \Delta\{\sqrt{(R^2 + X^2)}\} - X$ using the length of the short side or the diameter $2R$ of the ultrasonic wave transmission surface as a parameter. If a point is below this graph, it is in a near acoustic field, and if a point is above, it is in a far acoustic field.

Fourth Preferred Embodiment ~~embodiment~~

[089] ——— In this fourth preferred embodiment, an examination has been made on various characteristics of the ultrasonic wave transmitter/receiver having the configuration of the third preferred embodiment of the present invention shown in Fig. 9 and Fig. 10.

[090] ——— Fig. 14 shows the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water temperature, using the ultrasonic transmitter/receiver 20 having the configuration shown in Fig. 9. In this regard, the value at 70°C is indicated as 0 nsec here. Also, the calculated value in the same figure was obtained from the distance $X \approx 1.4$ mm between the ultrasonic transducers 1a and 1b and the document value. As is understood from Fig. 14, the difference between the measured result and the calculated value is small, and that repeated measurement precision is outstanding~~good~~.

[091] Figs. 15A and 15B show ~~Fig. 15 shows~~ the results obtained by measuring ultrasonic wave propagation time in water, which changes with the water temperature, using the ultrasonic transmitter/receiver 21 having the configuration shown in Fig. 10. In this regard, Fig. 15A~~the same figure (a)~~ is the case of integrating a pair of ultrasonic transducers 1a and 1b, and the spacer 22 by bonding with epoxy resin. Also, Fig. 15B~~the same figure (b)~~ is the case of integrating a pair of ultrasonic transducers 1a and 1b, and the spacer 22 by bonding with glass.

[092] ——— The comparison Figs. 15A and 15B~~of both of them~~ shows that the one in which the spacer 22 is bonded with glass has a smaller error from the document value, and a better repetition precision. On the other hand, the one in which the spacer 22 is bonded with epoxy resin has larger variations and a~~the~~ difference from the document values. Thus, it is unsuitable~~inappropriate~~ for the case of demanding high time

resolution. The reason for this is inferred that the distance between the pair of ultrasonic transducers 1a and 1b has changed by the deformation of the resin due to the change of the water temperature.

Fifth Preferred Embodiment~~embodiment~~

[093] ——— In this fifth preferred embodiment, in the case of using the ultrasonic transmitters/receivers 20 and 21 having the configuration of the third preferred embodiment shown in Fig. 9 and Fig. 10, for example, as shown in Fig. 16, ~~there is sometimes~~ a partition wall 25, such as a pipe, is disposed between the pair of ultrasonic transducers 1a and 1b, and a substance 24, such as a liquid or other suitable substance, is, ~~etc., to be~~ the target of measurement of the sound speed. The influence to that partition wall 25 is examined. Here, a polycarbonate having a thickness $L_w = 0.2$ mm was used for the partition wall 25, and water was used for the substance 24 through which an ultrasonic wave propagates. The sound speed in the polycarbonate ~~to be the~~ partition wall 25 was about 2,330 m/s.

[094] ——— Fig. 17A~~(a)~~ is a result obtained by measuring the propagation of an ultrasonic wave in a state of dipping in water the ultrasonic transmitter/receiver 20 having the configuration shown in Fig. 9 without change. Fig. 17B~~(b)~~ is a result obtained by measuring the propagation of an ultrasonic wave in a state of disposing a partition wall 25 between the ultrasonic transmitter/receiver 20 and water 24. In Figs. 17A~~(a)~~ and 17B~~(b)~~,

a curve in the upper row is the waveform of a drive pulse of an amplitude of about 4.5 V and a time width of about 100 nsec. A curve in the middle row is a waveform produced by amplifying the signal propagated to the ultrasonic transducer 1a of the receiving side ~~20 times the signal propagated to the ultrasonic transducer 1a of the receiving side~~. A curve in the lower row is produced by enlarging the portion marked by a reference numeral P of the curve in the middle row. In this regard, adhesive, such as epoxy resin, silicon rubber or other suitable adhesive, etc., ~~etc.,~~ are thinly applied to the ultrasonic transmitter/receiver 20 and the partition wall 25.

[095] ——As is understood from Figs. 17A and 17B. ~~17~~, the transmission and receiving of an ultrasonic wave are possible even if there is a partition wall 25, and significant variations are not produced ~~cannot be seen~~ in the amplitude of the received waveform. However, when there is a partition wall 25 between the ultrasonic transmitter/receiver 20 and water 24, as shown in Fig. 18, ultrasonic waves are received both from the direct wave emitted from the transmission surface of the ultrasonic transducer 1b of the transmission side and the ultrasonic wave reflected on the end surface of the partition wall 25. Fig. 17B ~~(b)~~ shows a state of having received both of such direct wave and the ultrasonic wave reflected on the end surface of the partition wall. Accordingly, when the direct wave and the reflected wave are received in an overlapping state, it is ~~becomes~~ difficult to detect the zero-cross point with high precision.

[096] ——— In order to separate the direct wave emitted from the transmission surface of the ultrasonic transducer 1b of the transmission side and the ultrasonic wave reflected on the end surface of the partition wall 25, ~~it is necessary that~~ the time T_w required for going to and coming back in the partition wall 25 ~~must be greater~~^{is longer} than the pulse width T_d of the drive pulse ($T_w > T_d$). Accordingly, in Fig. 18, assuming that L_w is the thickness of the partition wall 25 and V_w is the sound speed propagated in the partition wall 25, $T_w = 2L_w/V_w$. Thus, if the thickness L_w of the partition wall 25 is set to satisfy $2L_w/V_w > T_d$, namely the above-described condition (4), ~~it is possible to separate~~ the direct wave and the reflected wave are separated in time, ~~and to detect~~ the zero-cross point can be detected with high precision.

[097] ——— From such a viewpoint, the measurements were made on the propagation of the ultrasonic wave in the case of the partition wall 25 made of a polycarbonate having thicknesses of about 0.2 mm and about 0.5 mm, respectively. The results are ~~result is shown~~ in Figs. 19A and 19B.~~19.~~ Fig. 19A(a) is the case of the partition wall 25 having the thickness $L_w = 0.2$ mm. Fig. 19B(b) is the case of the partition wall 25 having the thickness $L_w = 0.5$ mm. In each of the figures, a curve in the upper row is the waveform of a drive pulse of an amplitude of about 4.5 V and a time width of about 100 nsec. A curve in the middle row is a waveform produced by amplifying the signal propagated to the ultrasonic transducer 1a of the receiving side

~~20 times the signal propagated to the ultrasonic transducer 1a of the receiving side.~~ A curve in the lower row is produced by enlarging the portion marked by a reference numeral P of the curve in the middle row. As shown by the comparison of Figs. 19A~~(a)~~ and 19B~~(b)~~, if the thickness L_w of the partition wall 25 is set to satisfy the condition of the above-described (4), it is understood that the influence of the reflected wave on the direct wave is eliminated.

Sixth Preferred Embodiment~~embodiment~~

[098] ——— In this sixth preferred embodiment, as in the above-described fifth preferred embodiment, the influence of the material of the partition wall 25 has been examined when there is a partition wall 25 such as a pipe, ~~etc.,~~ between the pair of ultrasonic transducers 1a and 1b, and a substance 24 to be the target of measuring the sound speed.

[099] ——— Here, the measurements were made on the propagation state of the ultrasonic waves using a polycarbonate and a liquid crystal polymer as a material of the partition wall 25, individually, the partition wall 25 has a thickness $L_w = 0.5$ mm in both of the cases, and water is used as the substance 24 through which the ultrasonic wave propagates. The results ~~are~~~~result is~~ shown in Figs. 20A and 20B. Fig. 20A. ~~Fig. 20(a)~~ is the case of the partition wall 25 made of a polycarbonate, and Fig. 20B. ~~(b)~~ is the case of the partition wall 25 made of a liquid crystal polymer. In each of the figures, a curve in the upper

row is the waveform of a drive pulse of an amplitude of about 4.5 V and a time width of about 100 nsec. A curve in the middle row is a waveform produced by amplifying the signal propagated to the ultrasonic transducer 1a of the receiving side 20 times~~the signal propagated to the ultrasonic transducer 1a of the receiving side~~. A curve in the lower row is produced by enlarging the portion marked by a reference numeral P of the curve in the middle row. As is understood from this result, it is possible to transmit and receive ultrasonic waves using not only a polycarbonate but also a liquid crystal polymer as the material of the partition wall 25, and the S/N ratio thereof is outstanding~~good~~.

[0100] ———As shown in Fig. 21, both of the materials, a polycarbonate and a liquid crystal polymer, defining to be the partition wall 25 has an acoustic characteristic impedance value between the acoustic characteristic impedance of the piezoelectric ceramic constituting the ultrasonic transducers 1a and 1b and the acoustic characteristic impedance of the substance 24 (here, water) to be the target of the ultrasonic wave transmission. Accordingly, ~~it is possible to reduce~~ the amount of attenuation by the reflection of the ultrasonic wave on the partition wall 25 is reduced, and thus, ~~it is possible to transmit~~ an ultrasonic wave into the receiving side efficiently transmitted to the receiving side.

[0101] ———In this regard, when the ultrasonic transmitters/receivers 20 and 21 shown in Fig. 9 or Fig. 10 are

actually used, for example a flow tube 27 having a shape as shown in Figs. 22A-22C. ~~22~~ can be used. Fig. 22A~~(a)~~ is a partially cutaway front view showing the state in which the ultrasonic transmitter/receiver is attached, Fig. 22B~~(b)~~ is a side view thereof, and Fig. 22C~~(c)~~ is a sectional view taken along line Y-Y of Fig. 22A~~(a)~~.

[0102] — This flow tube 27 is made of a polycarbonate, has a rectangular flow path 27a provided ~~formed inside in~~ along the longitudinal direction, and has concave portions 27b and 27c provided ~~formed~~ on the right side and the left side, respectively. By attaching each of the ultrasonic transducers 1a and 1b of the ultrasonic transmitters/receivers 20 and 21 shown in Fig. 9 or Fig. 10 ~~as opposed~~ in each of the concave portions 27b and 27c, ~~it is possible to measure~~ the sound speed of the liquid flowing through the flow path 27a can be measured.

[0103] — By using such a flow tube 27, when measuring the flow speed of a corrosive liquid flowing through the flow path 27a, ~~it is possible to measure~~ the flow speed can be measured without deteriorating the reliability of the ultrasonic transmitters/receivers 20 and 21. Also, for example by attaching an integrated circuit having a function of measuring a temperature, ~~additionally, it is possible to constitute~~ an integrated module of the flow tube 27, the ultrasonic transmitters/receivers 20 and 21, and the integrated circuit is provided. Also, by having such a structure, it is possible to omit the spacer member 22 shown in Fig. 10, and thus, ~~it is~~

~~possible to have a simpler configuration is provided.~~

[0104] ——— In this regard, in the above-described first to sixth preferred embodiments, piezoelectric ceramic is preferably used for the piezoelectric body 3 of the ultrasonic transducers 1, 1a and 1b. However, the present invention is not limited thereto. to this. For example, it is possible to use ~~apply~~ a high molecular PVDF piezoelectric body, or other suitable material ~~the like.~~

~~Industrial Applicability~~

[0105] ——— A method of driving an ultrasonic transducer according to preferred embodiments of the present invention can be used for an ultrasonic transducer to measure ~~in the case of measuring~~ a sound speed propagating in a medium such as a liquid or other medium ~~the like.~~

[0106] While preferred embodiments of the present invention have been described above, it is to be understood that variations and modifications will be apparent to those skilled in the art without departing the scope and spirit of the present invention. The scope of the present invention, therefore, is to be determined solely by the following claims.

——— ~~Fig. 1 illustrates the configuration of an ultrasonic transducer in a first embodiment of the present invention. Fig. 1(a) is a sectional view, and Fig. 1(b) is a sectional view taken along line Z-Z of Fig. 1(a).~~

——— ~~Fig. 2 is a planar sectional view illustrating the specific~~

~~size and shape of the electrode of the ultrasonic transducer shown in Fig. 1.~~

~~—— Fig. 3 is a configuration diagram of an apparatus used for observing the received waveform of the ultrasonic wave transmitted from the ultrasonic transducer having the configuration shown in Fig. 1.~~

~~—— Fig. 4 is an explanatory diagram in the case of applying a drive pulse of the ultrasonic transducer using the same apparatus.~~

~~—— Fig. 5 is a diagram showing the received waveform of the ultrasonic wave obtained when the pulse width of the drive pulse of the ultrasonic transducer is changed using the apparatus shown in Fig. 3.~~

~~—— Fig. 6 is a characteristic diagram showing the result of the measurement of each sound pressure of a mountain peak and a valley peak of the received waveform of the ultrasonic wave obtained when the pulse width of the drive pulse of the ultrasonic transducer is changed using the apparatus shown in Fig. 3.~~

~~—— Fig. 7 is an explanatory diagram illustrating a relationship between the ultrasonic wave directly emitted from the emission surface of the piezoelectric resonator and the ultrasonic wave emitted by being reflected from the open end surface of the backing layer and passing through the piezoelectric resonator 2 again in the ultrasonic transducer having the configuration shown in Fig. 1.~~

~~—— Fig. 8 is an explanatory diagram illustrating the comparison~~

~~between the drive pulse applied to the ultrasonic transducer and the waveform of the received ultrasonic wave.~~

~~—— Fig. 9 is an explanatory diagram in the case of configuring an ultrasonic transmitter/receiver by placing opposite a pair of ultrasonic transducers driven with the configuration and the condition described in a first and a second embodiments at a predetermined distance.~~

~~—— Fig. 10 is an explanatory diagram in the case of configuring another ultrasonic transmitter/receiver by placing opposite a pair of ultrasonic transducers driven with the configuration and the condition described in a first and a second embodiments at a predetermined distance.~~

~~—— Fig. 11 is an explanatory diagram in the case of setting an opposed distance in order to separate the direct wave and the diffracted wave generated with ultrasonic emission in the ultrasonic transmitter/receiver shown in Fig. 9 or Fig. 10.~~

~~—— Fig. 12 is a characteristic diagram showing the received waveform generated when the opposed distance between a pair of ultrasonic transducers in Fig. 11 is changed.~~

~~—— Fig. 13 is a graph plotting $\Delta = \{\sqrt{(R^2 + X^2)}\} - X$ using the length of the short side or the diameter $2R$ of the ultrasonic wave transmission surface as a parameter.~~

~~—— Fig. 14 is a characteristic diagram showing the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water temperature, using the ultrasonic transmitter/receiver having the configuration shown in Fig. 9.~~

~~—— Fig. 15 is a characteristic diagram showing the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water temperature, using the ultrasonic transmitter/receiver having the configuration shown in Fig. 10.~~

~~—— Fig. 16 is an explanatory diagram schematically illustrating the situation in the case where there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.~~

~~—— Fig. 17 is a characteristic diagram showing a result obtained by measuring the propagation situation of the ultrasonic wave depending on the existence of a partition wall using the ultrasonic transmitter/receiver having the configuration shown in Fig. 9.~~

~~—— Fig. 18 is an explanatory diagram schematically illustrating the situation in the case where an ultrasonic wave is reflected by the existence of the partition wall when there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.~~

~~—— Fig. 19 is a characteristic diagram showing the result obtained by measuring the propagation situation of the ultrasonic wave with partition walls having different thicknesses when there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.~~

~~—— Fig. 20 is a characteristic diagram showing the result obtained by measuring the propagation situation of the ultrasonic wave in accordance with the difference of the material of a partition wall using the ultrasonic transmitter/receiver having~~

~~the configuration shown in Fig. 9.~~

~~—— Fig. 21 is an explanatory diagram showing relationships among the density, the sound speed, and the acoustic characteristic impedance of various materials.~~

~~—— Fig. 22 illustrates a flow tube to be applied when the ultrasonic transmitter/receiver shown in Fig. 9 or Fig. 10 is used. Fig. 22(a) is a partially cutaway front view showing the state in which the ultrasonic transmitter/receiver is attached, Fig. 22(b) is a side view thereof, and Fig. 22(c) is a sectional view taken along line Y-Y of Fig. 22(a).~~

~~—— Fig. 23 is a timing chart showing relationships among a drive pulse, received ultrasonic waveforms, and measurement pulses when the sound speed in a substance is measured using the ultrasonic transducer.~~

~~—— Fig. 24 is a waveform chart to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in a method of driving an ultrasonic transducer of the present invention.~~

~~—— Fig. 25 is a waveform chart to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in the method of driving the ultrasonic transducer of the present invention.~~

~~—— Fig. 26 is a waveform chart to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in the method of driving the ultrasonic transducer of the present invention.~~

~~Reference Numerals~~

~~1, 1a, 1b ultrasonic transducers~~

~~2, 2a, 2b piezoelectric resonators~~

~~3 piezoelectric body~~

~~31, 31a, 31b piezoelectric active portions~~

~~4, 4a, 4b electrodes~~

~~5, 5a, 5b electrodes~~

~~20, 21 ultrasonic transmitters/receivers~~

~~24 substance to be the target of sound speed measurement~~

~~25 partition wall~~